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The role of ionospheric clutter in mid-latitude and arctic regions for assessment of HFSWR surveillance

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The role of ionospheric clutter in mid-latitude and arctic regions for the assessment of HFSWR surveillance

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Abstract

The ionosphere is the region of the earth's atmosphere in which gases are ionized by radiation such as ultraviolet light from the sun and cosmic rays from outer space. The unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. This paper studies the arctic and mid-latitude ionospheric environment using ionosonde data and assesses High-Frequency Surface-Wave Radar (HFSWR) surveillance for surface vessels and low-altitute air targets. Although there are various types of ionospheric clutter, in this study we concentrate only on the sporadic-E (Es) ionospheric clutter. The evaluation is based on sporadic-E interference in the HFSWR signal. Our studies show that the Es is reasonably common in the arctic regions. The best time to perform HFSWR surveillance is between approximately 06:00-15:00 UT and 20:00-00:00 UT. During these hours, the number of days that sporadic-E interference occurs in a month and the range of frequencies reflected is minimized compared to other times of the day. Of the sites considered, Resolute Bay is the most favourable site for HFSWR surveillance in the summer since sporadic-E interference occurs least often, resulting in reduced signal interference. Similarly, Eureka is the preferred site during the winter months. In addition, the ionosphere at Eureka generally reflects the lowest range of maximum frequencies ($\sim 4 - 8$ MHz), again resulting in less clutter interference. In all the observations, polar cap sites Eureka and Resolute Bay yield results that are less prone to sporadic-E interference than the mid-latitude site Cambridge Bay. The general behaviour of the morphology of polar cap Es that is observed in this study is explained by gravity waves and metallic ions.

Résumé

L'ionosphère est cette région de l'atmosphère terrestre dans laquelle les gaz sont ionisés par des rayonnements comme la lumière ultraviolette du Soleil et les rayons cosmiques venant de l'espace. L'expression fouillis ionosphérique regroupe la totalité des échos radars indésirables renvoyés par l'ionosphère. Cette communication porte sur l'étude de l'ionosphère au-dessus de l'Arctique et aux latitudes moyennes, au moyen de données recueillies par ionosondes, et évalue la surveillance des navires de surface et des cibles aériennes à basse altitude par radar haute fréquence à ondes de surface (HFSWR). Même s'il y a plusieurs types de fouillis ionosphériques, cette étude porte essentiellement sur le fouillis ionosphérique sporadique E (Es). L'évaluation est basée sur l'interférence sporadique E dans le signal du HFSWR. Nos études démontrent que le fouillis Es est passablement commun dans les régions arctiques. Le meilleur moment pour effectuer de la surveillance HFSWR se situe entre 6h et 15 h UT puis à 20 h UT. Pendant ces périodes, le nombre de jours où l'interférence sporadique E se produit en un mois de même que la plage des fréquences réfléchies est moindre comparativement aux autres heures de la journée. Parmi tous les sites envisagés, la baie Resolute est le site le plus favorable pour la surveillance HFSWR en été puisque l'interférence sporadique de type E étant moins fréquente, l'interférence de signaux est réduite. De même, Eureka est le site idéal pendant les mois d'hiver. De plus, l'ionosphère à Eureka réfléchit généralement la plage inférieure des fréquences maximales ($\sim 4 - 8\text{MHz}$) ce qui une fois de plus réduit l'interférence causée par le fouillis. Dans toutes les observations que nous avons effectuées, les sites de Eureka et de la baie Resolute prés de la calotte polaire donnent des résultats qui sont moins sensibles à l'interférence sporadique E que celui de la baie Cambridge qui se trouve à une latitude moyenne. Le comportement général de la morphologie du fouillis ionosphérique Es observé dans le cadre de cette étude s'explique par les ondes de gravité et par les ions métalliques.

Executive summary

The unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. It has proved to be the greatest impediment to achieving consistently good performance in long-range detection and tracking of surface vessels for HFSWR [1-3]. Although sophisticated signal processing techniques have been developed to minimize the interference, the effectiveness of these techniques is highly dependent on the characteristics of the ionospheric clutter. Ionospheric clutter can mask target echoes having similar Doppler shifts. That is, HFSWR signals are Doppler shifted as they are refracted and reflected in the ionosphere, resulting in a broad band near zero Doppler shift. This is a major limitation in the detection of line-of-sight low-speed targets [1-3].

This report investigates the statistical characteristics of ionospheric clutter conditions and compares ionosonde measurements in the mid-latitude and arctic regions in determining the most favourable conditions for the HFSWR surveillance of surface and low-altitude targets. This assessment is based primarily on ionosonde data collected in mid-latitude and arctic regions. Although there are several types of ionospheric clutter, in this study we concentrate only on the sporadic-E ionospheric clutter.

Our studies show that the Es is reasonably common in the arctic regions. The best time to perform HFSWR surveillance is between approximately 06:00-15:00 UT and 20:00-00:00 UT. During these hours, the number of days that sporadic-E interference occurs in a month and the range of frequencies reflected is minimized compared to other times of the day. Of the sites considered, Resolute Bay is the most favourable site for HFSWR surveillance in the summer since sporadic-E interference occurs least often, resulting in reduced signal interference. Similarly, Eureka is the preferred site during the winter months. In addition, the ionosphere at Eureka generally reflects the lowest range of maximum frequencies ($\sim 4 - 8$ MHz), again resulting in less clutter interference.

The general behaviour of the morphology of polar cap Es that is observed in this study is explained by gravity waves and metallic ions. The general conclusion of this paper is that operation of HFSWR at selected locations in the arctic should be feasible, at least less prone to sporadic-E interference than mid-latitude sites. This conclusion is based primarily on sporadic-E ionospheric clutter. In future studies, we intend to investigate the ionospheric clutter associated with F layer. In addition, we shall develop methods and algorithms to mitigate the detrimental effects of these ionospheric clutters.

Sommaire

Le fouillis ionosphérique regroupe la totalité des échos radars indésirables renvoyés par l'ionosphère. Ce fouillis s'est révélé le plus grand obstacle à l'obtention d'une bonne performance constante dans la détection à longue portée et la poursuite des navires de surface par HFSWR [1-3]. Même si des techniques de traitement de signaux de haute technicité ont été élaborées pour réduire les effets de l'interférence, l'efficacité de ces techniques dépend étroitement des caractéristiques du fouillis ionosphérique. Le fouillis ionosphérique peut masquer les échos de cible ayant des décalages Doppler similaires. Cela veut dire que les signaux du HFSWR subissent un décalage Doppler quand ils sont réfractés puis réfléchis dans l'ionosphère. Le résultat étant un décalage Doppler quasi-nul en bande large. Il s'agit là d'une restriction majeure pour la détection de cibles volant à faible vitesse en visibilité directe [1-3].

Le présent rapport étudie les caractéristiques statistiques des conditions de fouillis ionosphérique et compare les mesures prises par ionosondes dans les régions arctiques et aux latitudes moyennes, en déterminant les conditions les plus favorables pour effectuer de la surveillance des navires de surface et des cibles à base altitude par HFSWR. Cette évaluation est basée essentiellement sur les données recueillies par ionosondes dans les régions arctiques et aux latitudes moyennes. Même s'il y a plusieurs types de fouillis ionosphérique, cette étude ne porte que sur le fouillis ionosphérique sporadique de type E.

Nos études démontrent que le fouillis de type Es et plutôt courant dans les régions arctiques. Le meilleur moment pour effectuer de la surveillance HFSWR se situe entre 6h et 15 h UT puis à 20 h UT. Pendant ces périodes, le nombre de jours où l'interférence sporadique E se produit en un mois de même que la plage des fréquences réfléchies est moindre comparativement aux autres heures de la journée. Parmi tous les sites envisagés, la baie Resolute est le plus favorable pour la surveillance HFSWR en été puisque l'interférence sporadique de type E étant moins fréquente, l'interférence de signaux est réduite. De même, Eureka est le site idéal pendant les mois d'hiver. De plus, l'ionosphère à Eureka réfléchit généralement la plage inférieure des fréquences maximales ($\sim 4 - 8\%$ MHz), ce qui une fois de plus réduit l'interférence causée par le fouillis.

Le comportement général de la morphologie du fouillis ionosphérique Es observé dans le cadre de cette étude s'explique par les ondes de gravité et par les ions métalliques. La conclusion générale du rapport est que l'exploitation du HFSWR à des endroits précis dans l'Arctique devrait être réalisable, du moins serait-il moins sensible à l'interférence sporadique de type E que sur des sites à des latitudes moyennes. Cette conclusion repose essentiellement sur le fouillis ionosphérique sporadique de type E. Dans le cadre de prochaines études, nous comptons étudier le fouillis ionosphérique associé à la couche F. De plus, nous envisageons de développer des méthodes et des algorithmes qui permettront de réduire les effets nuisibles de ces fouillis ionosphériques.

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1. INTRODUCTION

Microwave radars are the sensors traditionally used to establish continuous offshore surveillance. Shore-based microwave radars operate in line-of-sight mode and cannot detect and track surface vessels and low-flying aircraft much beyond 50 km because of the line-of-sight limitation in the propagation of microwave signals. Because of the curvature of the earth, low-altitude and surface targets promptly drop below the horizon for most ground-based microwave radars. For surveillance of surface vessels and low-flying aircraft beyond 50 km, the only alternative up to now has been to operate from shipboard and airborne platforms, where the costs of providing surveillance are very high and 24-hour, all-weather surveillance is simply not practical.

High-Frequency (HF) radars are sometimes referred to as over-the-horizon radars (OTHRs) because of their capability to receive target echoes over much longer distances than microwave radars. The most common type of OTH radar operates in the sky-mode, which receives radar echoes through reflection from the ionosphere. The High-Frequency Surface-Wave Radar (HFSWR), on the other hand, utilizes the surface-wave mode of propagation for target detection. Because surface waves propagate efficiently only for vertical polarization over a conducting surface, HFSWR is practical only for coastal installations, where the ocean surface serves as the conductor. This unique capability allows the HFSWR to be the only shore-based radar system capable of detecting small surface vessels and low-flying air targets at tactically significant ranges. For long-range applications HFSWR operates at relatively low frequencies (2-6 MHz) to avoid the large attenuation of the surface wave at the upper HF frequencies [1-2]. For an HF sky-wave radar, the ionosphere is a necessary medium for its operation. For an HFSWR, however, the ionosphere represents a source of interference that is detrimental to its performance.

HFSWR is an effective and relatively low-cost means of providing over-the-horizon surveillance of surface vessels and low-flying aircraft in coastal regions. These radar systems have demonstrated the capability to detect and track surface vessels beyond 400 km range and small low-flying aircraft out to 120 km range [1-3]. Thus, these systems can be used to monitor activity within the full range of the Exclusive Economic Zone (EEZ). The technology offers highly autonomous 24-hour-per-day, 7-day-per-week operation with one of the lowest operating costs per unit coverage area of all other radar types.

The Canadian Department of National Defence (DND) has engaged in research and development of HFSWR technology for the past fifteen years. One of the objectives of this program is to demonstrate the potential of employing HFSWR technology as a means for providing wide-area coastal surveillance of surface vessels and low-flying air targets in mid-latitude and arctic regions [1-4]. An operational HFSWR must be able to operate in a congested signal spectrum with limited signal bandwidth, and in the presence of sea clutter, ionospheric interference and external man-made noise. Before an operational HFSWR system can be implemented in the arctic region, it must

demonstrate capability in a wide range of signal and physical environments.

Our previous studies show that one of the dominant clutters that degrade the detection capability of surface and low-flying targets using HFSWR is ionospheric clutter [1-3]. The unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. It has proved to be greatest impediment to achieving consistently good performance in long-range detection and tracking of surface vessels for HFSWR. The performance of HFSWR is significantly affected by ionospheric clutter while radar signals are reflected and received. Although sophisticated signal processing techniques have been developed to minimize the interference, the effectiveness of these techniques is highly dependent on the characteristics of the ionospheric clutter. Ionospheric clutter can mask target echoes having similar Doppler shifts. That is, HFSWR signals are Doppler shifted as they are refracted and reflected in the ionosphere, resulting in a broad band near zero Doppler shift. This is a major limitation in the detection of line-of-sight low-speed targets [1-3].

This report investigates the statistical characteristics of ionospheric clutter conditions and compares ionosonde measurements in the mid-latitude and arctic regions in determining the most favourable conditions for the HFSWR surveillance of surface and low-altitude targets. This assessment is based primarily on ionosonde data collected in mid-latitude and arctic regions. Although there are several types of ionospheric clutter, in this study we concentrate only on the sporadic-E ionospheric clutter. We intend to investigate the other types of ionospheric clutter in a future publication.

2. Experimental HFSWR facilities

The HFSWR at Cape Race is a monostatic pulse Doppler radar, capable of operating in the 3-5 MHz radio frequency range. The radar employs a log-periodic transmit antenna, and a linear and uniform receive antenna array of 16 doublet elements. The transmitter antenna floodlights the ocean surface off the east cost of Newfoundland. The receiving doublets, each consisting of two kite-shaped monopoles, are phased end-fire to receive the radar backscatter from the ocean surface. The separation between adjacent doublets is 33.33 m (radar design frequency: 4.5 MHz). The boresight of the receiving array is aimed at the direction of 121° clockwise from true north. Using digital beamforming, the receiving array provides azimuth coverage between $-60°$ and $+60°$ [1-4].

The HFSWR at Cape Bonavista has a similar setup. However, a quadlet, instead of a doublet, is used as a receiving element in the radar at Cape Bonavista. The boresight of the receiving array at Cape Bonavista is aimed at the direction of $110°$ clockwise from the true north. The azimuth coverage of the radar is also between $-60°$ and $+60°$ [1-2]. A more detailed description of the radar systems is given in [3-4].

3. The Ionosphere, Ionosonde and Sporadic E

The long-range surveillance of ships and aircraft by sky-wave radar would not be possible without the existence of the ionosphere. However, one of the major limitations for HFSWR surveillance is the presence of ionospheric clutter. The unwanted reflection of the radar signal from the ionosphere has proven to be the greatest impediment in achieving consistently good performance in long-range detection and tracking of surface vessels by a high-frequency surface-wave radar. These unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. There are many factors that cause ionospheric clutter including auroras, meteor trails, ionospheric layers and sporadic E [1-3,5-9]. It is this last case that we will consider in detail.

3.1 Ionosphere

The Earth's ionosphere, a partial ionized magnetoplasma, is produced by photons and particles that are emitted from the sun and which ionize a portion of the neutral upper atmosphere. The lowest altitude at which ionization is encountered is about 60 km and it extends from there to many earth radii. The region between 90 km and 400 km is the most important for OTHR since it is at these altitudes that electromagnetic wave reflection is significant. In this region, the bulk of the ionization is caused by the action of extreme UV and X-rays on atoms and molecules of oxygen and nitrogen [5].

The varying frequency bands of the sun's emission and the physical chemistry of the atmosphere are jointly responsible for relatively distinct ionospheric regions or layers. Those most significant for OTHR operation are designated the D, E and F layers. The D layer does not contribute to the ionospheric clutter because it basically acts as an absorbing layer for HF signals. During the day, the absorbing D layer is present, preventing long-range propagation in the lower part of the HFSWR band. The E layer occurs from 90-150 km with an ionization peak around 105 km and provides useful OTHR (sky-mode) propagation during the day to about 1800 km. Above this lies the F layer, within which there are frequently separate layers. The most important layer for OTHR (sky-mode), because it is the most intense layer in the ionosphere, is designated the F2 layer and peaks at around 300 km. An important feature of the F2 layer is that it is sustained throughout the night by ion transport and the low ionization recombination rate. The ability of a layer to reflect radio waves is related to its electron density, which defines the layer plasma frequency [5].

As far as the HFSWR is concerned, echoes from the ionosphere are unwanted signals. Ionospheric clutter remains a major problem for HFSWR that operates at ranges corresponding to the heights of the E and F layers. It is important that these reflections can be distinguished from legitimate targets.

3.2 Ionospheric Sounding

The Appleton-Hartree formula describes the propagation of radio waves in a uniformly magnetized medium [5,10]. Considering the Appleton-Hartree equation, assume that the ionosphere is unmagnetized plasma and no collisions are taking place, then the refractive index is given by

$$n^2 = 1 - f_n^2/f^2$$

(1)

where f_n is the plasma frequency and f is the wave frequency [5]. The plasma frequency f_n (Hz) is defined by

$$f_n = 9\sqrt{N}$$

(2)

where N is electron density (electrons per m^3) [5]. If the plasma frequency is greater than the wave frequency, the wave cannot propagate since the refractive index is imaginary. In this case, the wave will be reflected back to Earth. The plasma frequency is also known as the critical frequency, because its value is the limit at which radio waves are either reflected or refracted.

The theory behind the Appleton-Hartree formula is an important factor in the operation of the ionosonde. An ionosonde, or ionospheric sounder, is a device used to determine the structure of ionospheric layers by transmitting short pulses of radio waves vertically upwards towards the ionosphere. The transmitter and receiver sweeps the typical frequency range from 1 MHz to 20 MHz and measures the length of time for the wave to reflect off the ionospheric layers and return to Earth. Taking the speed of the wave to equal approximately to the speed of light, c, the virtual height of the reflecting layer is given by

$$h' = ct/2$$

(3)

where t is the measured time and c is the velocity of the light [10]. The virtual height is the altitude at which the wave is reflected if there is no refraction. If the transmitted frequency is greater than the critical frequency, the wave will penetrate the ionospheric layer without being reflected. However, its path will be refracted by the ionization present and its time-of-flight will increase. If the wave has a lower frequency than the critical frequency of a higher layer, it will be reflected and a further delay will result as it travels back through the ionization once again. Hence, the virtual height will always be greater than the true height. To obtain true height values, the ray path must be reconstructed using information about the electron concentration along the ray path. True height analysis was introduced to present the different analysis required to obtain true height values from the ionosonde [10]. However, this is not a key topic in this report so it will not be discussed further.

Ionograms are the output of the ionosonde. They are the traces of reflected radio pulses, and this output results from the fact that strata of the ionosphere have different plasma

frequencies. If the frequency of the radio pulse is greater than the critical frequency of the ionospheric layer, the layer will not reflect the pulse, and no echo will be seen on the ionogram. The frequency of the radio wave constitutes the x axis, and the height of the corresponding ionospheric layer constitutes the y axis (Figure 1).

3.3 Sporadic E

Sporadic E (Es) is a thin, erratically occurring layer that forms in the earth's ionosphere, and is most prevalent between 90 and 150 km altitude [7-9]. Clouds of abnormally intense ionization that are able to reflect signal frequencies up to 20 MHz frequently form in the vicinity of the ionospheric E layer. The clouds are small, ranging from 50 km to 150 km in diameter. They may be circular, long and thin, or take on irregular shapes. These clouds occur quite randomly and dissipate within a few hours, hence they are known as sporadic-E ionization clouds, or simply Es. The Es behaviour is related to the combined effects of the orientation of the magnetic field, electric field, neutral winds, wave motions and distribution of metallic ions [7-8]. Its production mechanism is quite different at middle, low and high latitudes. Es in the low and middle latitudes occurs mostly during the daytime and early evening, and is more prevalent during the summer months. At high latitudes, Es tends to form at night.

High-latitude Es has been the subject of many recent papers. These have shown that the Es usually occurs close to the height where there are strong negative gradients in the vertical ion motion. This vertical motion is due to the combined effects of neutral winds and drift due to electric fields. At high-latitude the effects of the electric field usually dominate [11-12]. The vertical motion due to the electric field is proportional to $\cos I$, where I is the magnetic dip [11]. Thus for a typical high-latitude station with $I = 80^o$ the vertical component is only about 17 % of the horizontal component of motion. This small vertical component of motion is, however, significant because of the relatively large magnitude of the horizontal motion due to electric fields at high latitudes [11, 13-18]. The predominately horizontal neutral winds also cause a small vertical movement of ionization; however, while this wind-driven movement dominates the vertical motion, and thereby the Es behaviour, at middle and low latitudes, it is usually less effective than the electric field at high latitudes.

As well as the effects of electric fields and neutral winds, the Es behaviour is also related to the distribution of metallic ions [19]. Es is often observed to be in the form of several hours, and such layers have been shown both observationally, and from modelling, to be composed mostly of Fe^+ and Mg^+ ions, with smaller concentration of Na^+ ions [20]. Indeed, many of the modelling studies of Es only consider the effect of vertical motions on an initially thick layer of metallic ions [21-22].

The studies referred to [11-21] used data mainly from the following stations, listed with their magnetic dip values: Sondrestrom ($I = 80^o$), EISCAT ($I = 76^o$), and Casey ($I = -82^o$). These dip values for these stations were determined from the NSSDC Web site which calculates the IGRF (International Geomagnetic Reference Field) from the

station coordinates, height, and year [23]. The typical value of $\cos I$ for these stations is $\cos 80^o = 0.17$. In the study presented here the stations used are Eureka ($I = 88.1^o$) and Resolute Bay ($I = 86.5^o$). A dip of 88°, $\cos I = 0.034$, which is only about 1/5 the typical value of the earlier studies. One might speculate that Es should be relatively uncommon at these central polar cap stations with such low values of $\cos I$. However, as shown in this report, thin flat layers of Es are relatively common during summer in the northern central polar cap stations.

Recently, [8] described a model that has been used to explain the morphology of polar cap Es. This model incorporates several features, including the results of recent laboratory studies on metallic ion recombination. The initial Es is assumed to be produced by gravity waves interacting with metallic and ambient NO^+ and O_2^+ ions. This produces transient ionization enhancements in the E region. In the winter night, these enhancements undergo dissociative recombination with electrons and disappear, but in summer reionization of the metallic atoms by charge exchange with ambient E region ions can maintain Es as thin intense layers at an altitude of about 100 km for many hours. A more detailed explanation for the Es morphology is presented in [8].

Es, which can be the most intense layer in the ionosphere, has several important effects on HFSWR. First, it can severely obscure the performance of HFSWR at ranges corresponding to the heights of the Es. Second, because of its erratic temporal and spatial nature, Es is very hard to predict and consequently can play havoc with the accuracy of HFSWR.
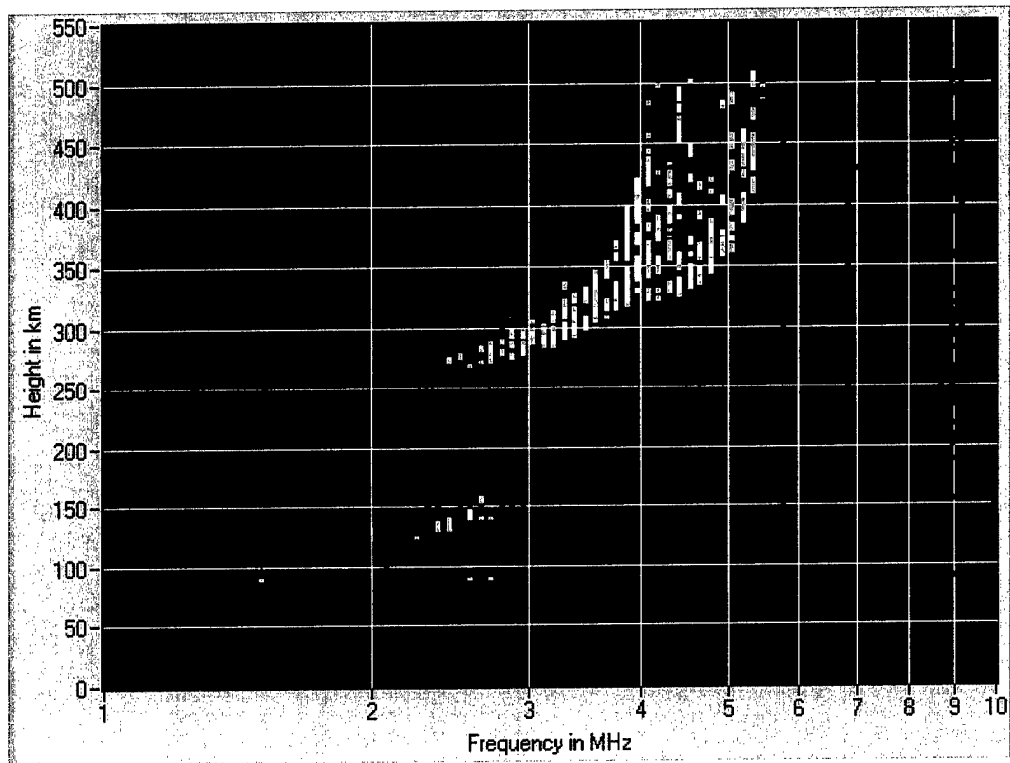
Figure 1: *The distinct layers of the ionosphere can be seen in the ionogram. The first layer is the E layer. The region above 150 km contains the F layer, the most important reflecting layer. The ionogram was taken on January 31, 2000, hour 00:00 UT at Cape Race.*

4. Results

The Canadian Advanced Digital Ionosonde (CADI) was developed by the University of Western Ontario as part of the Canadian Network for Space Research program. These ionosondes have been installed in a number of polar cap, auroral zone, and mid-latitude locations. In this study, we concentrate on the data collected at mid-latitude locations of Cape Race (46.39°N, 53.06°W) and Cambridge Bay (69.10°N, 105.11°W) and polar cap locations of Resolute Bay (74.75°N, 94.99°W) and Eureka (79.99°N, 85.92°W). Figure 2 shows the geographical location of the four sites. The ionosondes recorded ionograms at 95 frequencies from 1.7 to 19 MHz. During the winter months the usual sampling protocol was an ionogram each minute. During the summer the sampling interval for the ionograms was different for each station because of operational constraints [7]. Figure 1 shows a typical ionogram at Cape Race. We note that at the lowest frequencies the signals are returned from the E layer. At frequencies above approximately 3 MHz the wave penetrates the E layer and is reflected from the F layer.

The data from these stations show that Es is a reasonably frequent phenomenon. The Es that we observed could usually be assigned to one of three types [7].

(a) Auroral Es: This is usually a short-lived patch of Es (lasts for typically 10 minutes) and usually has a diffuse appearance on the ionogram. We often see the patch approach, pass over, and then recede from the station as the auroral structure passes overhead. In general, auroral Es is seen at these stations only for a very small fraction of time. We will not be concerned with this type of Es in this report.

(b) Thin Es: This Es can prevent signals from reaching the upper layers and is known as blanketing. Figure 3 shows an ionogram displaying a blanketing Es formation. This type of Es takes the form of flat intense layers that have a similar appearance to "flat" or "low" types of Es that are seen at lower latitudes. These thin intense layers are usually have a thickness of about 15 km or less.

(c) Height-spread Es: We sometimes see an Es that extends over a range of heights on the ionograms. An example is shown in Figure 4. The Es is the band of echoes extending to 7 MHz with a lower height of 110 km, and having an apparent thickness of about 40 km. Since F-layer echo can be seen above the Es, the Es is not blanketing, which implies that it is probably in the form of patches (in the horizontal dimension) with gaps between them. We call this "height-spread" Es. This type of Es takes the form of moving patches.

Similar to the ionogram, the HFSWR measures the time for the echo to reach the receiver, hence the range of the target can be easily determined. The HFSWR also measures the Doppler shift of the signal and can thus determine the radial speed of the target. Figure 5 is an example of sea and ionospheric clutter measured at 4.1 MHz at hour 02:00 UT using Cape Race HFSWR. Sea-clutter components are concentrated around ±0.19 Hz Doppler with two narrow spectral spikes. In the case of HFSWR used over the ocean, the sea clutter is due to Bragg scattering from ocean waves. The
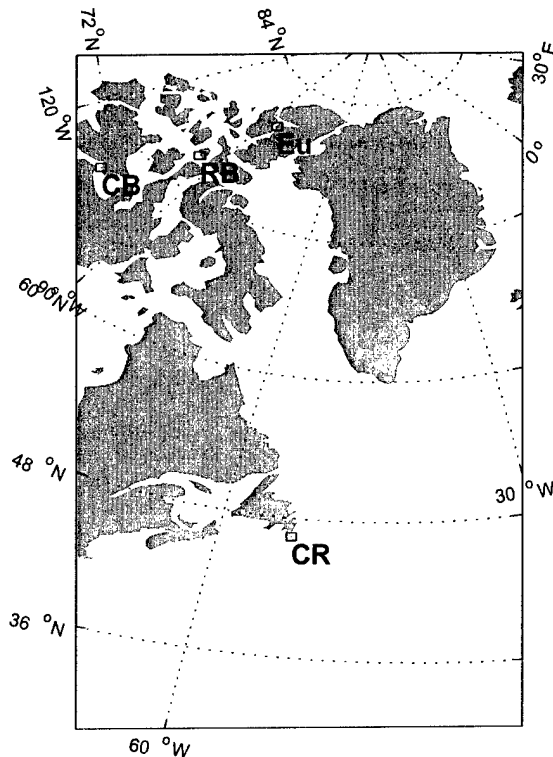
Figure 2: *Geographic location of the four sites: CR - Cape Race. CB - Cambridge Bay, RB - Resolute Bay and Eu - Eureka.*

spectral peak on the left hand side of Figure 5 is called the receding Bragg line. The one on the right hand side is called the advancing Bragg line. The Bragg lines appear as two very large targets. This is a major limitation in detection of low-speed surface targets like ships and icebergs. When a low-altitude maneuvering aircraft travels in a direction tangential to the radar beam, the aircraft target can appear in the velocity spectrum close to the sea-clutter-dominated region. This limits the detection of line-of-sight low-speed air targets [1-2, 24-27]. We will not be further concerned with sea clutter in this report.

The clutter at around 325 km in Figure 5 results from the direct reflection from the ionosphere's F layer, and which is so strong that it usually bounces between the Earth and the ionosphere several times, creating a band of clutter in the radar on each bounce. The ionogram for the same hour is then checked to see if the reflection is due to ionospheric F layer. Figure 6 shows that at 4.1 MHz, a dense F layer is present in the vicinity of 325 km. Therefore we conclude that the HF reflection is due to the ionospheric F layer. The absence of E-layer clutter above 3.5 MHz allows the radar to have long-range detection performance. It should be noted that the ionosonde and the HFSWR are co-located within a kilometer at Cape Race. Figure 5 also shows that the ionospheric F-layer reflection occupies a fairly broad Doppler extent around 0 Hz,

which is unfavourable because ship and aircraft echoes with the same Doppler shift as the layers will be masked. The ionospheric-clutter processes associated with the F layer have a significantly negative impact on radar performance against ships at long ranges. The magnitude of the ionospheric clutter associated with the F layer is generally much greater than that associated with the E layer. Most of the F-layer ionospheric-clutter processes occur at ranges beyond 200 km from the radar. At these ranges, the target magnitude is relatively small compared to that of the clutter.

Figure 7 shows another HFSWR data example of ionospheric clutter due to thin Es. The intense E layer reduces the performance of HFSWR at these ranges. The corresponding ionogram is shown in Figure 3. Figures 7 and 3 clearly show that the unwanted reflection of the radar signal from these thin Es affects achieving consistently good performance in detection and tracking of surface vessels by an HFSWR at these ranges. The Es are especially problematic since they can reflect a large range of frequencies. Therefore we must analyze the characteristics of these thin and height-spread Es to determine the ionospheric conditions that yield the minimal presence of Es.

In the following subsection we perform statistical analysis on the ionosonde data. We consider two variations of sporadic Es; (1) time of year (seasonal) and (2) time of day (diurnal). This will give a better idea of the variability of HFSWR detection statistics. Ionosphere data is available at Cambridge Bay in 1998 and 1999, Eureka from 1998 to 2000, and Resolute Bay from 1998 to 2000. Data sets with the best continuity are Cambridge Bay in 1998, Eureka in 1999, and Resolute Bay in 1999 and 2000, therefore these data sets will be used in the analysis. The summer months of Eureka in 1998 will also be analyzed. However, no data is available from October to December in 1998.
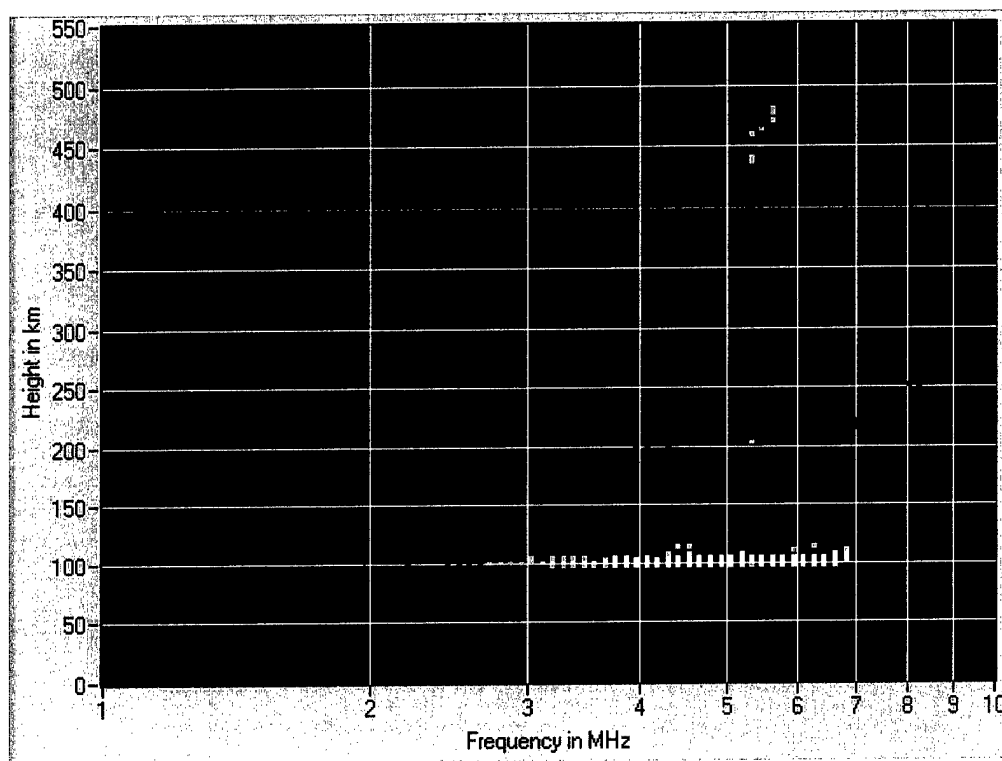
Figure 3: Thin sporadic-E blanketing; taken on August 29, 2000, hour 18:00 UT at Cape Race.
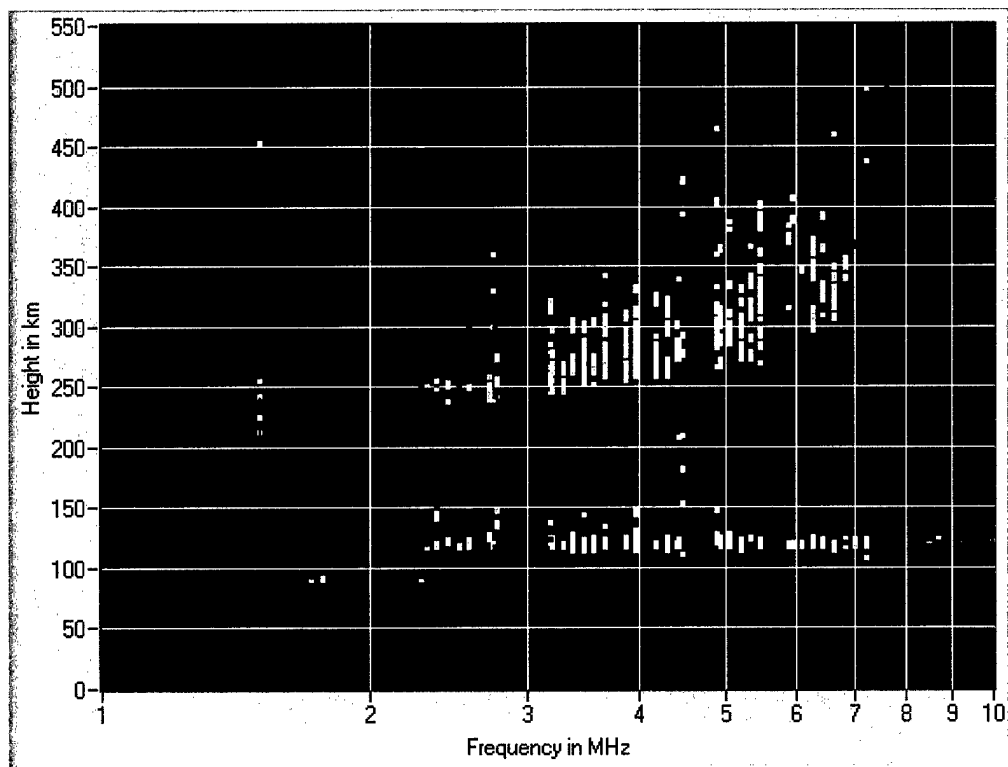
Figure 4: *Height-spread sporadic E; taken on August 28, 2000, hour 02:00 UT at Cape Race.*

Figure 5: HFSWR data with ionospheric F layer; taken on August 30, 2000, hour 02:00 UT at Cape Race. The unit of the colour bar is dB.

Figure 6: *Ionogram comparison to HFSWR data. The ionogram taken on August 30, 2000, hour 02:00 UT at Cape Race.*

Figure 7: HFSWR data with thin sporadic E; taken on August 29, 2000, hour 18:00 UT at Cape Race. The unit of the colour bar is dB.

4.1 Seasonal Es Variation
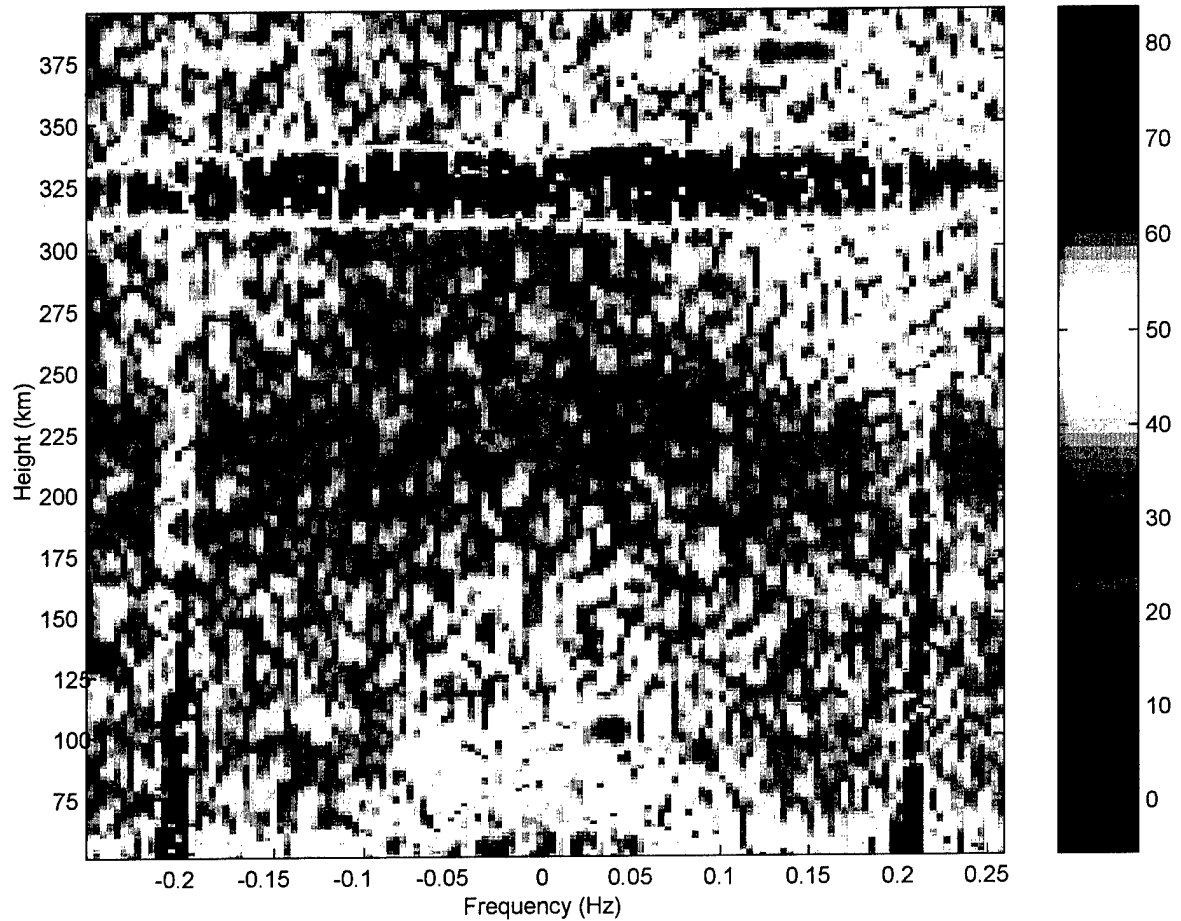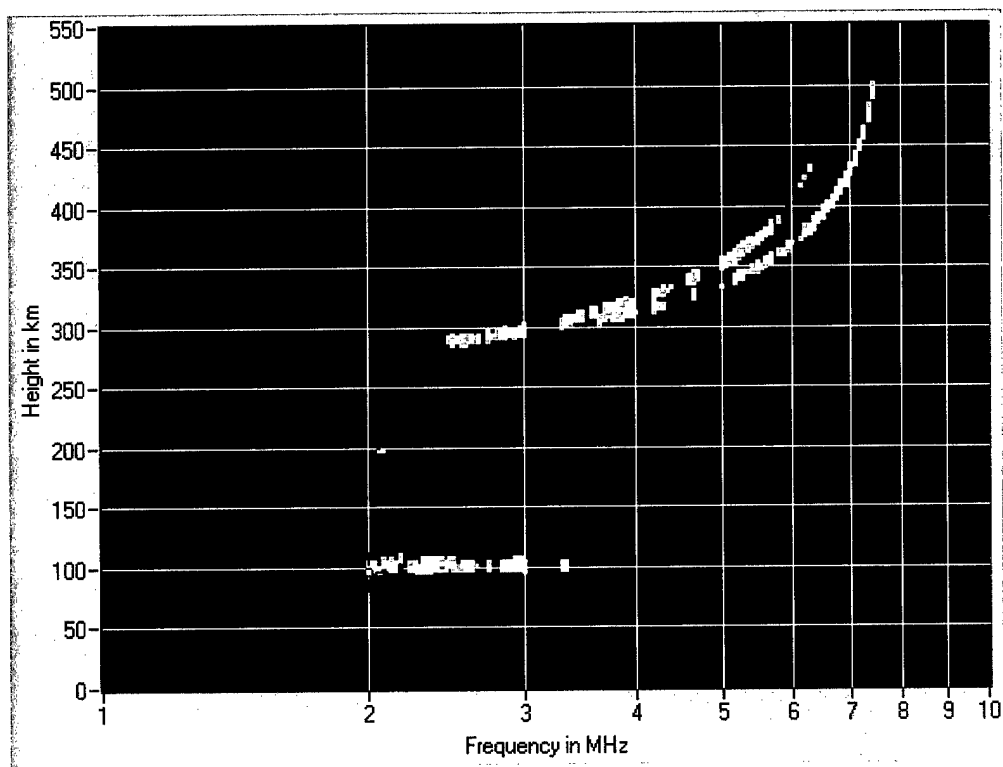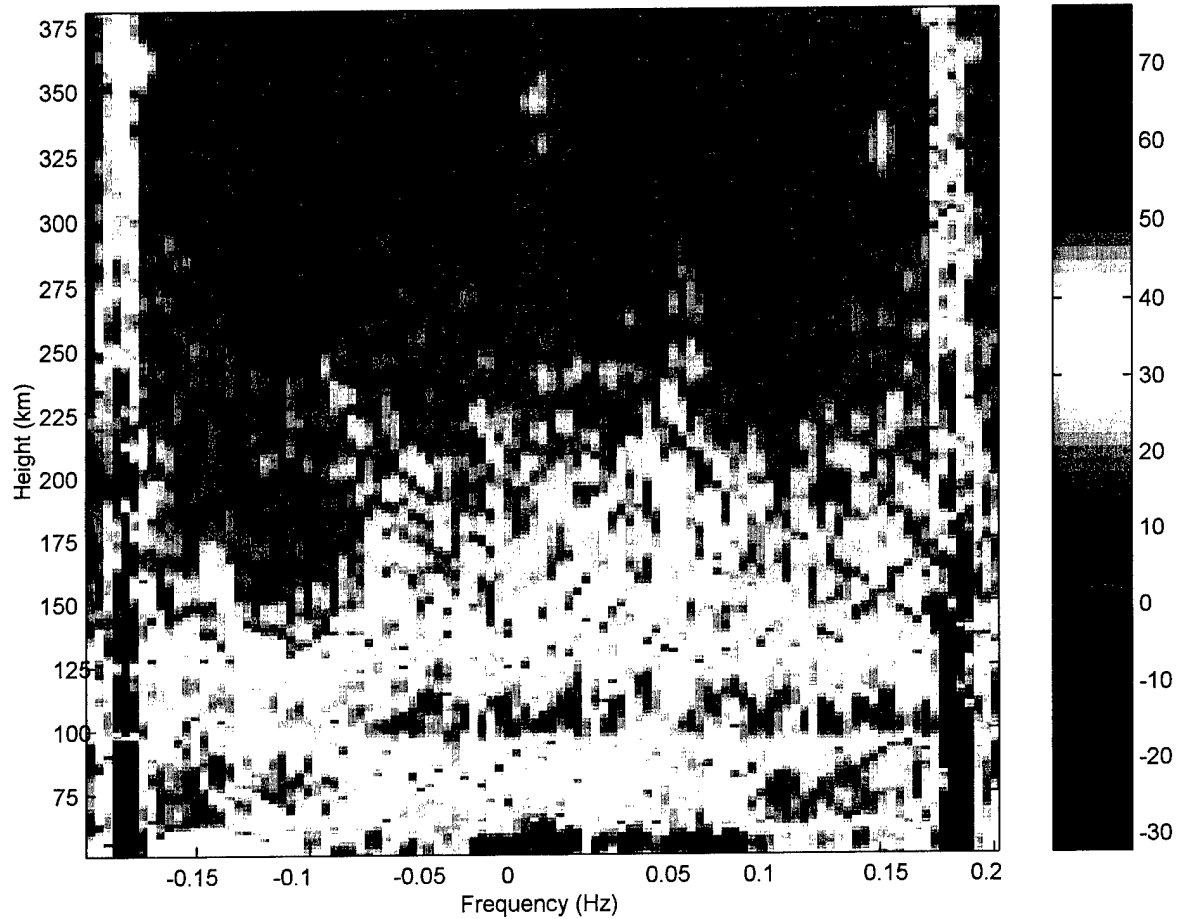
Figure 8 presents the number of height-spread and thin Es occurrences as a function of month in 1998 at Cambridge Bay and Eureka, respectively. Note that an occurrence was considered to take place if the Es lasted for more than 2 hours. Plots similar to Figure 8 have been studied for other sites and years, and Table 1 summarizes the results. Considering seasonal variations, height-spread Es occurred more often in the winter at Cambridge Bay and Resolute Bay, whereas they occurred more often in the summer at Eureka. Thin Es occurred more often in the summer months at all sites. Therefore the HFSWR performance in these period may decrease at these ranges corresponding to the heights of the Es as the season changes from winter to summer.

The most favourable site is the one in which there is the least amount of Es. Because of the fewest number of height-spread and thin Es, the ionospheric conditions for HFSWR surveillance are most favourable over Eureka in the winter and Resolute Bay in the summer. This conclusion is based only on ionospheric Es distribution. There are other factors for HFSWR surveillance such as propagation of HFSWR signals in an arctic environment, sea-clutter environment, etc. that can limit the performance of HFSWR in the arctic regions. However, those are not discussed in this report.

The general behavior of the morphology of polar cap Es that is observed in this study supports the recent model of polar cap Es [8]. The model can be explained as follows. The initial formation of Es is assumed to be produced by gravity waves interacting with metallic and ambient NO^+ and O_2^+, in both winter and summer. The vertical motion of the gravity waves is able to form Es by the downward transport of ions from lower F layer into the E layer. This produces transient ionization enhancements in the E layer. These concentrations are seen in winter as transient Es layers. In summer, these transient layers persist and change into long-lived thin Es layers because of metallic ions layers that are maintained in an ionized state by charge exchange of neutral metal atoms with the ambient E-layer ions produced by photo-ionization in the sunlit E layer. These thin intense Es layers occur at an altitude of about 100 km for many hours. A more detailed explanation for the model is presented in [8].
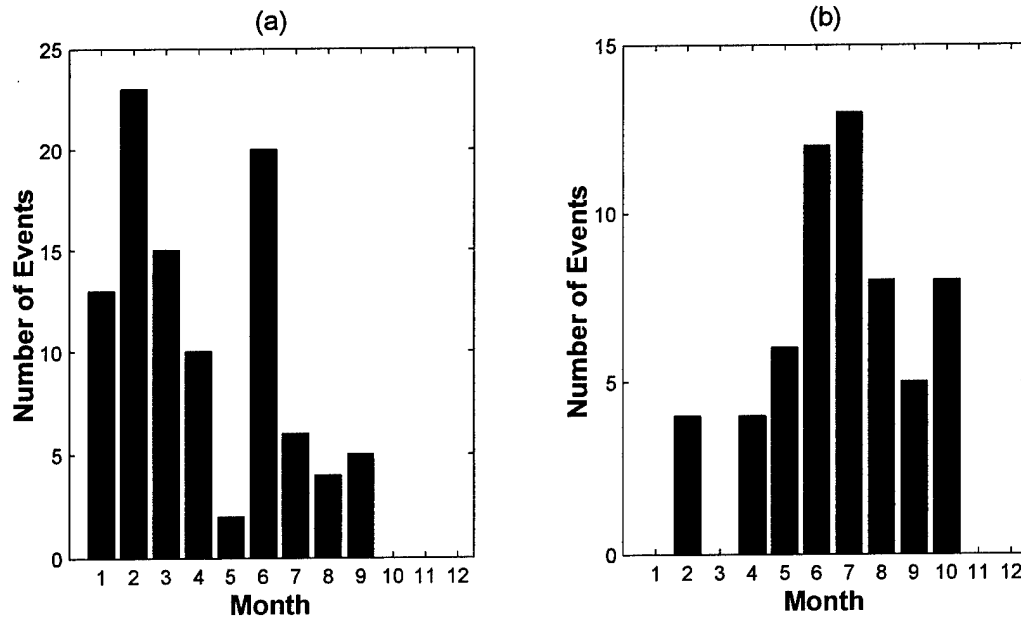
Figure 8: *Number of occurrences of in each month: (a) height-spread Es at Cambridge Bay in 1998 and (b) thin Es at Eureka in 1998.*

Table 1: *Seasonal sporadic-E variation.*

Site Name	Year	Approximate Number of Spread E Days per Month		Approximate Number of Thin E Days per Month	
		Winter	Summer	Winter	Summer
Cambridge Bay	1998	12-22	4-6	1-4	12
Eureka	1998	N/A	8-11	N/A	7-13
	1999	2-6	9-15	4-6	8-13
Resolute Bay	1999	11-16	6	0-3	1-6
	2000	12-18	4-7	0-3	3-6

4.2 Diurnal Es Variation

Figure 9 shows the occurrence statistics for the height-spread Es for the year 1998 at Cambridge Bay. The occurrence percentage is the number days with Es over the number of days that the data is received in a month (i.e., number of Es layers ÷ number of days of observation × 100). The total number of days of observation in each month is shown (in brackets after the month) in each panel of the figure. The determination is made on the basis of hourly averaged ionograms. Hours for which no data is plotted have 0% occurrence. This figure shows that the occurrence of height-spread Es maximizes during 04:00-07:00 UT. Figure 9 also shows that height-spread Es is maximum during the winter months (e.g., January, February and March) and minimum during the summer months. This seasonal variation may in part be due to the summer maximum of the thin Es (see Table 1). Thin Es tends to be blanketing and reflects at higher frequencies than height-spread Es, so it may obscure the presence of height-spread Es the during summer.

Plots similar to Figure 9 have been studied for other sites and years, and Table 2 summarizes the results for both the thin and height-spread Es. The table presents the hours and seasons that Es occurs most often, as well as the approximate percentage occurrence of the peaks. The height-spread Es tends to occur most during the hours 04:00 - 07:00 UT and 16:00 - 18:00 UT. Thin Es occurs most often between the hours of 15:00 and 20:00 UT, in the data where evident peaks can be observed. If no peaks are evident, the occurrence percentage in the table is the approximate occurrence percentage of the majority of the data for that month.

In general, the times during the day that will result in the most interference from Es are during 04:00-07:00 UT and 15:00-20:00 UT. All the sites have varying occurrence percentages, and this may be the result of poor data collection on certain months. Occurrence percentage depends on the number of days that the data is actually recorded. Thus, it should be noted that in a month where only one day of ionospheric data is recorded and it happens that a Es occurs on that day, the occurrence percentage for that month will spike up to 100.
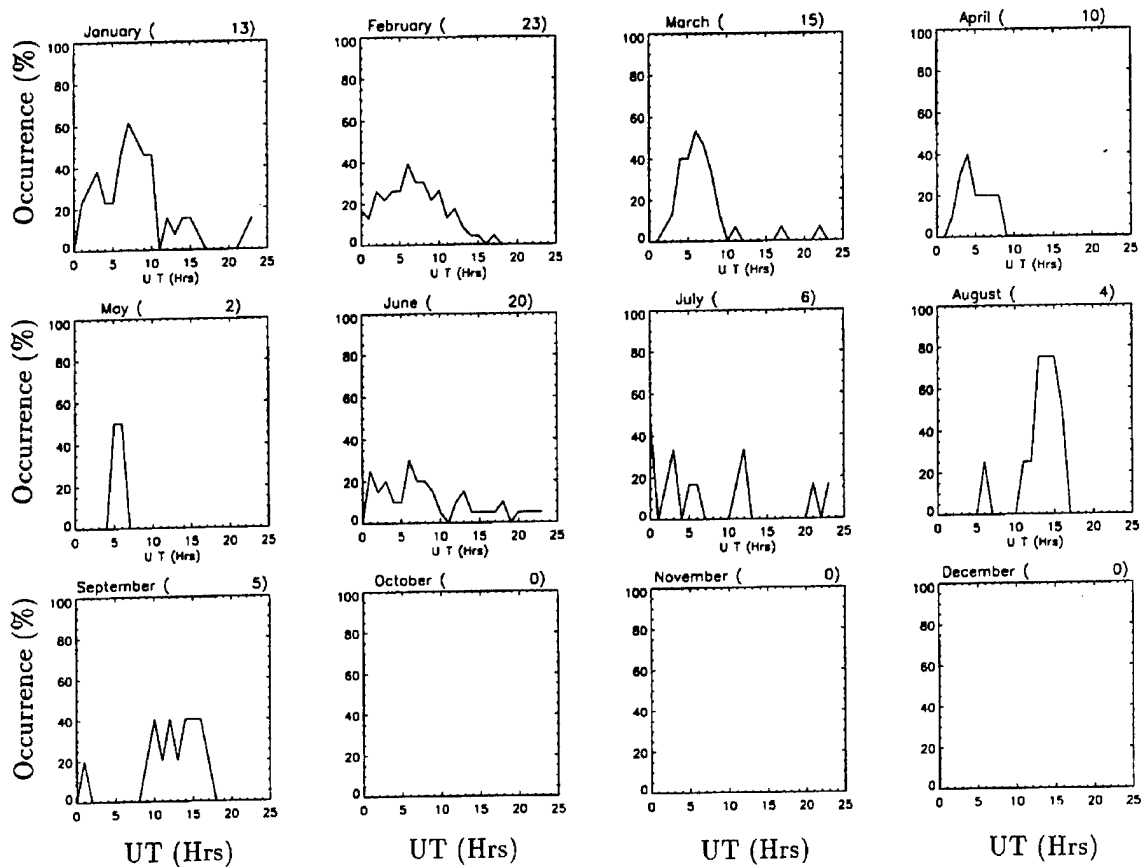
Figure 9: Occurrence statistics for the height-spread Es for the year 1998 at Cambridge Bay. The number of days of data collection is shown in brackets for each month.

Table 2: *Diurnal sporadic-E variation.*

Site Name	Year	Spread E Peak Hours		Thin E Peak Hours	
		Occurrence Percentage	Hours in the Day	Occurrence Percentage	Hours in the Day
Cambridge Bay	1998	40-60%	04:00-07:00 in winter months	20-40%	no evident peaks
Eureka	1998	20-40%	no evident peaks	60-75%	15:00-20:00 in summer months
	1999	20-40%	16:00-18:00 in summer months	40-60%	15:00-20:00 in summer months
Resolute Bay	1999	10-30%	no evident peaks	20-40%	no evident peaks
	2000	50-70%	04:00-07:00 and 16:00-18:00 in summer months	20-40%	no evident

4.3 Average Maximum Frequency

It is not only important how often ionospheric clutter occurs, but also the range of frequencies that can be reflected. Figure 10 shows the average maximum frequency reflected from the height-spread Es as a function of time of day at three sites in 1998. The average f_{max} (the critical frequency) is a measure of the peak electron density in the Es. Plots similar to Figure 10 have been studied for other years, and Table 3 summarizes the results for both the thin and height-spread Es. This table shows that the average of the maximum frequency reflected follows somewhat of a distinct trend in a single day. A large frequency band (8-15 MHz) is reflected in the late night hours (to obtain approximate LMT from UT substract 8 h) and the frequency drops in midday (4-8 MHz), and rises (8-18 MHz) again towards the evening hours 15:00-20:00 UT. It is easy to explain why one might expect higher critical frequencies around 20:00 UT since this is approximately local midday and one would expect higher ionospheric electron densities at this time. However, the second peak at about 00.00-05:00 UT is less easy to explain. We merely note that the time of this peak coincides with the time when this type of Es is most common, as seen in Table 1 particularly for Cambridge Bay and Resolute Bay sites.

The maximum average frequencies of the reflected signals from hours 00:00-05:00 UT and 15:00-20:00 UT are in the 8-18 MHz range, whereas reflected signals are in the 4-8 MHz range for the rest of the time. Hence, the first group of times limits the performance of HFSWR at these ranges corresponding to the heights of the Es. In addition, the smaller range of frequencies are reflected at Eureka than the other two sites for both the height-spread and thin Es. With the smaller range of frequencies being reflected, the ionospheric conditions for HFSWR surveillance are most favourable over Eureka in this regard.
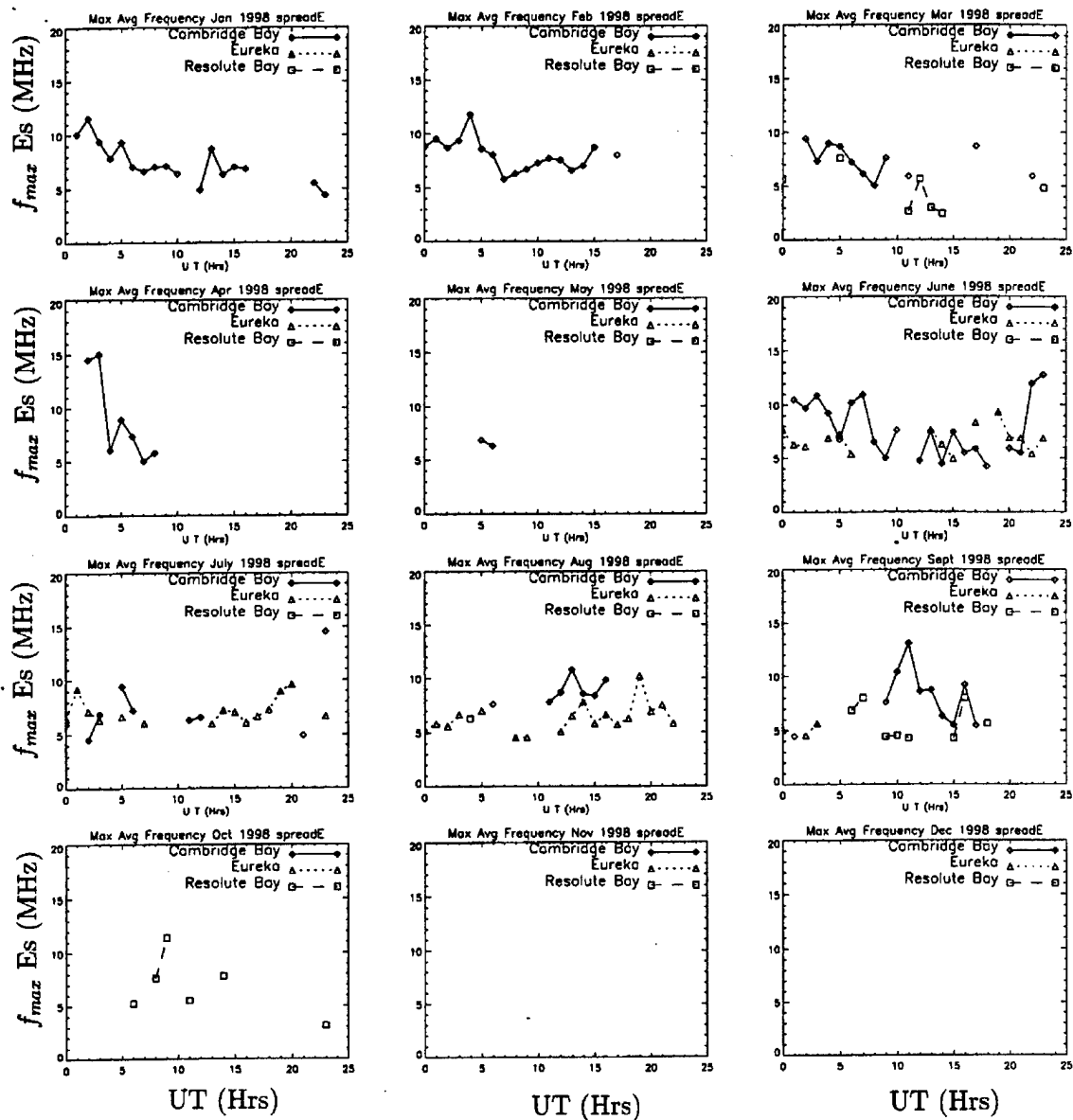
Figure 10: *Average maximum frequency reflected from the height-spread Es as a function of time of day at the three sites in 1998.*

Table 3: *Average maximum frequency trend.*

Site Name	Year	Spread E Frequency Range	Thin E Frequency Range
Cambridge Bay	1998	10-13 MHz at hrs 0-5 6-9 MHz at hrs 10-15	12-15 MHz at hrs 3-4 6-8 MHz at hrs 9-13
Eureka	1998	6-8 MHz at hrs < 18 10 MHz at hrs 19-20	5-8 MHz at all hours
	1999	8-12 MHz at hrs 0-7 5-6 MHz at hrs 7-15 8-13 MHz at hrs 15-20	10-15 MHz at hrs 0-5 4-6 MHz at hrs > 7
Resolute Bay	1999	12-15 MHz at hrs 0-5	no evident trends
	2000	10-15 MHz at hrs 3-8 5-7 MHz at hrs 8-14 13-18 MHz at hrs 15-20	no evident trends

4.4 Site Comparisons

An overview of the conclusions drawn from the analysis are the following: 1) Es occurs least often at Eureka in the winter and Resolute Bay in the summer, 2) the times during the day that will result in the most interference from Es are during 04:00-06:00 and 15:00-20:00 UT, 3) the largest frequency ranges are reflected by Es during hours of 00:00-05:00 and 15:00-20:00 UT, and 4) Eureka reflects the smallest range of frequencies compared to other sites. The best time to operate the HFSWR for good results is approximately 06:00-15:00 and 20:00-00:00 UT. One additional conclusion that can be made is that Es occurred less often in polar cap regions than at Cambridge Bay site. Thus Cambridge Bay is not the best site for any of the conditions considered. Arctic sites at Eureka and Resolute Bay exhibited more desirable traits for HFSWR surveillance. This conclusion is based primarily on ionospheric Es clutter.

5. Conclusion

This report studies ionospheric clutter conditions and compares ionosonde measurements in the mid-latitude and arctic regions to determine the most favourable conditions for HFSWR surveillance for surface vessels and low-altitude air targets. The evaluation is based primarily on sporadic-E (Es) interference in the HFSWR signal. Our studies find that there are different types of Es in winter and summer. The summer type is similar to common mid-latitude Es, being in the form of thin, intense layers in the lower E-region. The winter type takes the form of weaker short-lived layers in the middle to upper E-region. There is some occasional auroral Es but this is readily identifiable.

From the analysis of seasonal sporadic-E variation, the results show that Es occurs least often at Eureka in winter months where height-spread and thin Es are observed. Es occurs least often at Resolute Bay in summer months. On the other hand, at Cambridge Bay the height-spread Es occurs more often in winter months and thin Es in summer months. Thus the presence of Es at Cambridge Bay is consistently high at all times of the year. Therefore the long-range detection performance of the HFSWR at each site depends upon the season of year and location. The general behaviour of the morphology of polar cap Es that is observed in this study supports the recent polar cap model of Es [8].

Considering diurnal variations, the occurrence percentage of height-spread Es is found to be at a maximum during hours 04:00-06:00 and 16:00-18:00 UT. Thin Es occurrence maximizes at hours 15:00-20:00 UT in the months where peaks in the data are evident. This restricts the performance of HFSWR at ranges of heights from 100 to 150 km during these times of day, depending on the height of the Es layer reflections.

Results also show that the maximum average frequencies of the reflected signals during the hours 00:00-05:00 UT and 15:00-20:00 UT are in the 8-18 MHz range, whereas reflected signals are in the 4-8 MHz range for the rest of the time. Eureka is the site that reflected the smallest range of frequencies.

The general conclusion of this report is that operation of HFSWR at selected locations in the arctic should be feasible, at least less prone to sporadic-E interference than mid-latitude sites. This conclusion is based primarily on sporadic-E ionospheric clutter. In future studies, we intend to investigate the ionospheric clutter associated with the F layer. In addition, we shall develop methods and algorithms to mitigate the detrimental effects of these ionospheric clutters.

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(U) The ionosphere is the region of the earth's atmosphere in which gases are ionized by radiation such as ultraviolet light from the sun and cosmic rays from outer space. The unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. This paper studies the arctic and mid-latitude ionospheric environment using ionosonde data and assesses High-Frequency Surface-Wave Radar (HFSWR) surveillance for surface vessels and low-altitute air targets. Although there are various types of ionospheric clutter, in this study we concentrate only on the sporadic-E (Es) ionospheric clutter. The evaluation is based on sporadic-E interference in the HFSWR signal. Our studies show that the Es is reasonably common in the arctic regions. The best time to perform HFSWR surveillance is between approximately 06:00-15:00 UT and 20:00-00:00 UT. During these hours, the number of days that sporadic-E interference occurs in a month and the range of frequencies reflected is minimized compared to other times of the day. Of the sites considered, Resolute Bay is the most favourable site for HFSWR surveillance in the summer since sporadic-E interference occurs least often, resulting in reduced signal interference. Similarly, Eureka is the preferred site during the winter months. In addition, the ionosphere at Eureka generally reflects the lowest range of maximum frequencies ($\mathrm{\sim 4\text{-}8\%}$ MHz), again resulting in less clutter interference. In all the observations, polar cap sites Eureka and Resolute Bay yield results that are less prone to sporadic-E interference than the mid-latitude site Cambridge Bay. The general behaviour of the morphology of polar cap Es that is observed in this study is explained by gravity waves and metallic ions.

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